NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Clean Energy Technology: American and Global Progress

CU Energy Frontiers

Dr. Dan E. Arvizu, Laboratory Director

March 19, 2015

Energy Market Dynamics

Global renewable industry growing, but faces challenges

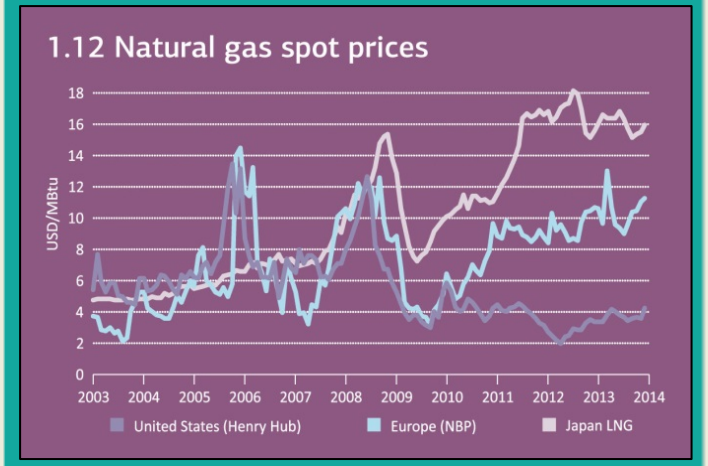
Public policy evolving—mostly local

Unconventional gas a growing focus with geographic disparities

Infrastructure investments will be made, must focus on flexibility

Technology is creating a platform for disruptive change

Updated 3/13/2015



A Profound Transformation is Required

Today's Unsustainable Energy System

- Limited fuel diversity
- Subject to price volatility
- Inefficient and rigid
- Significant carbon emissions
- Delivery systems vulnerable
- Aging infrastructure

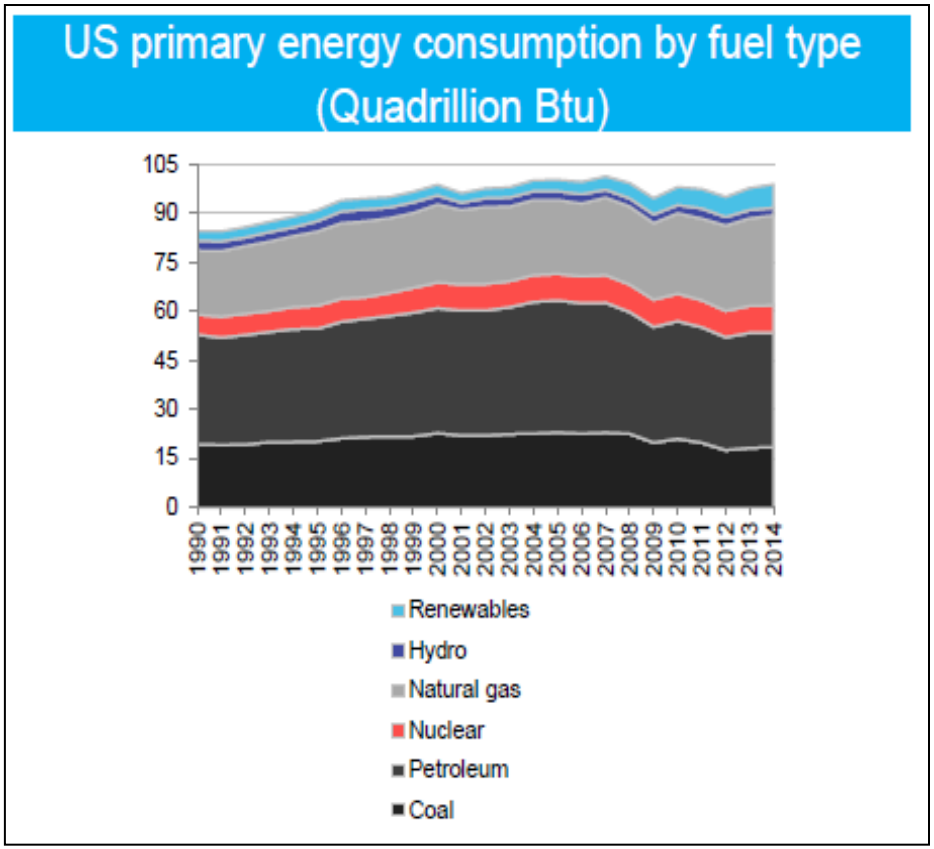
Future Sustainable Energy System

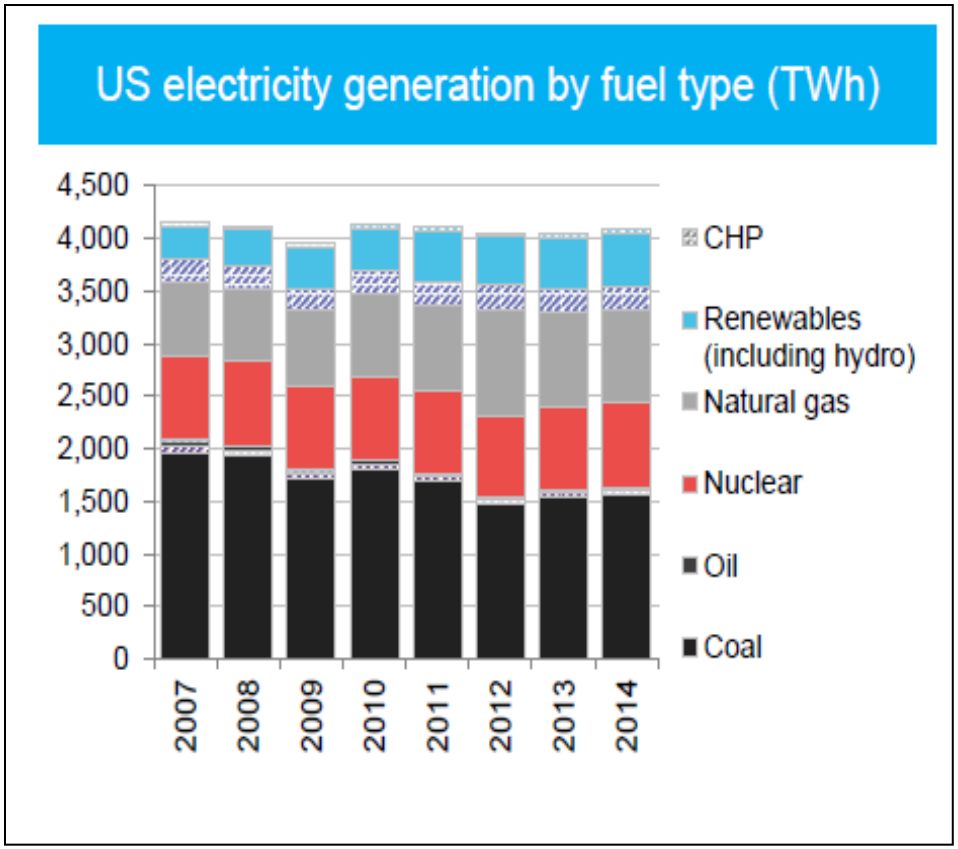
TRANSFORMATION

- Diverse supply options
- Affordable, stable and reliable
- Efficient and flexible
- Carbon neutral
- Secure and resilient
- More consumer driven

Updated 3/10/2015

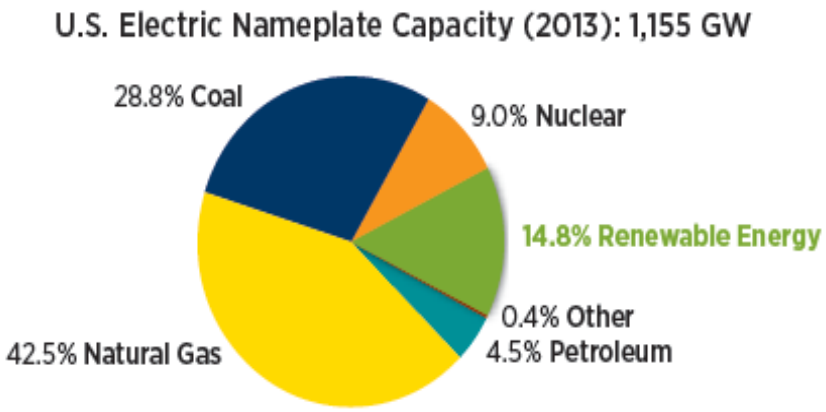
U.S. Consumption and Generation

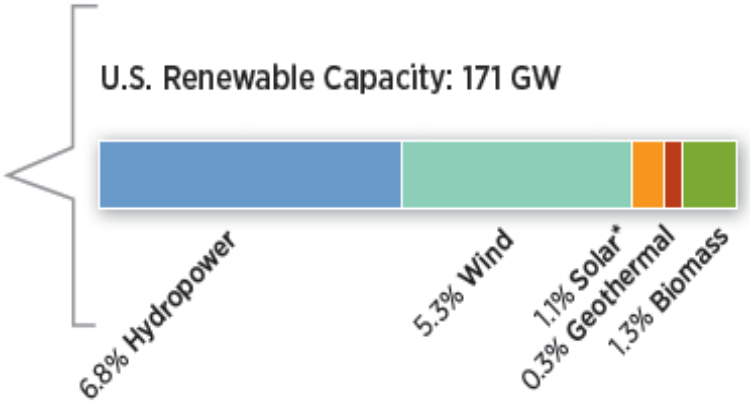


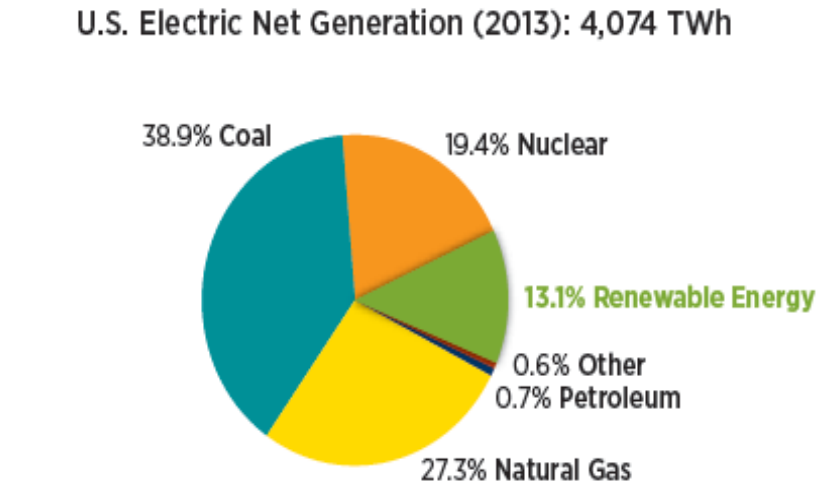


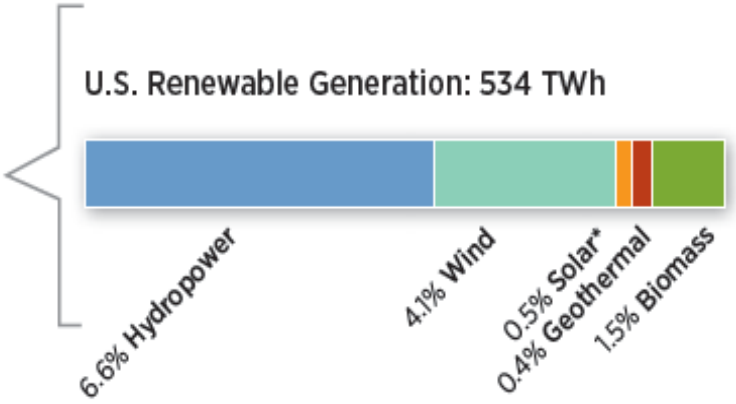
Source: http://www.bcse.org/images/2015%20Sustainable%20Energy%20in%20America%20Factbook.pdf

U.S. Electricity Nameplate Capacity and Generation









Sources: EIA, Larry Sherwood/Interstate Renewable Energy Council (IREC)

Other includes pumped storage, batteries, chemicals, hydrogen, pitch, purchased steam, sulfur, tire-derived fuels, and miscellaneous technologies.

*Grid-connected only

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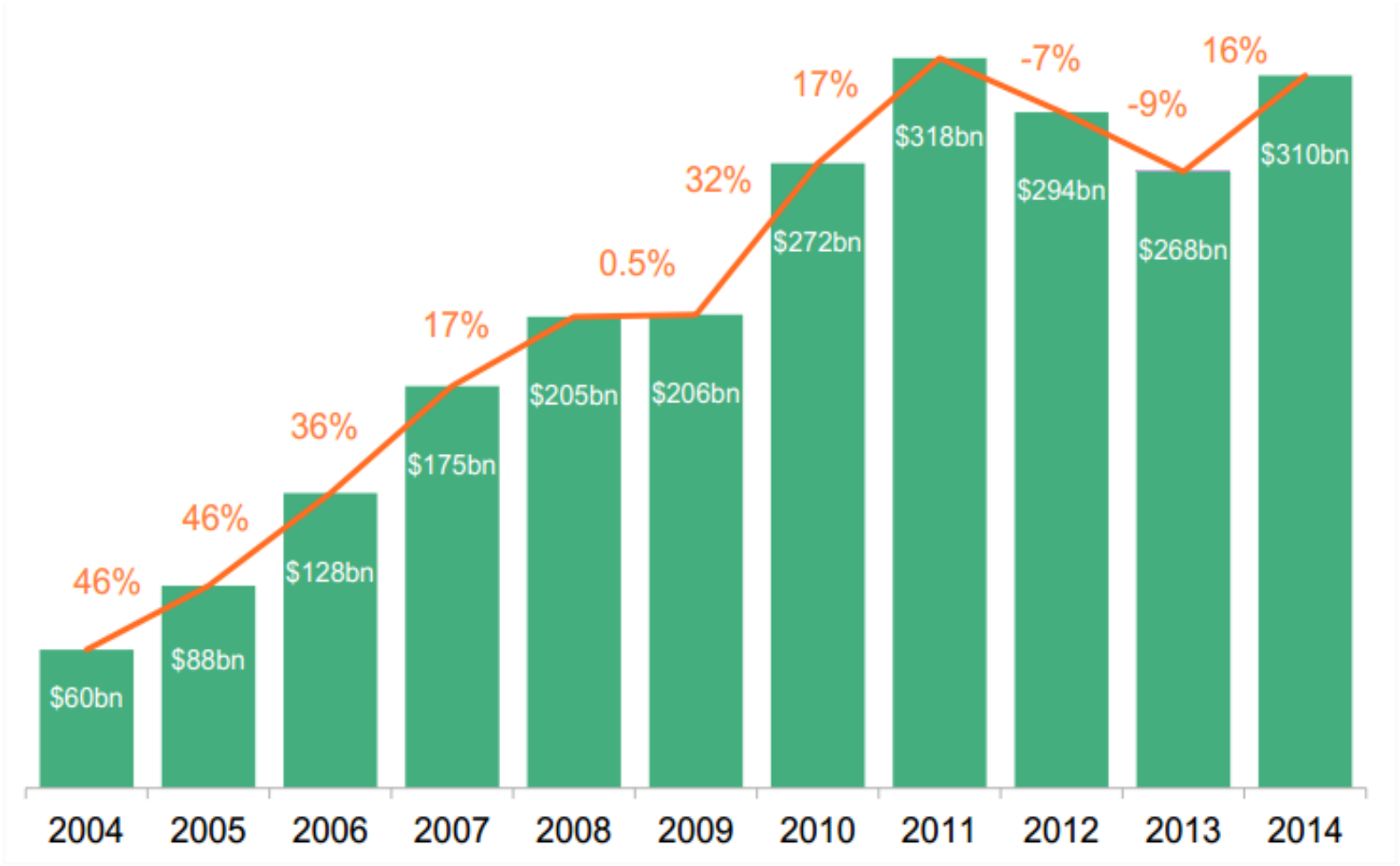
Source: NREL 2013 Data Book

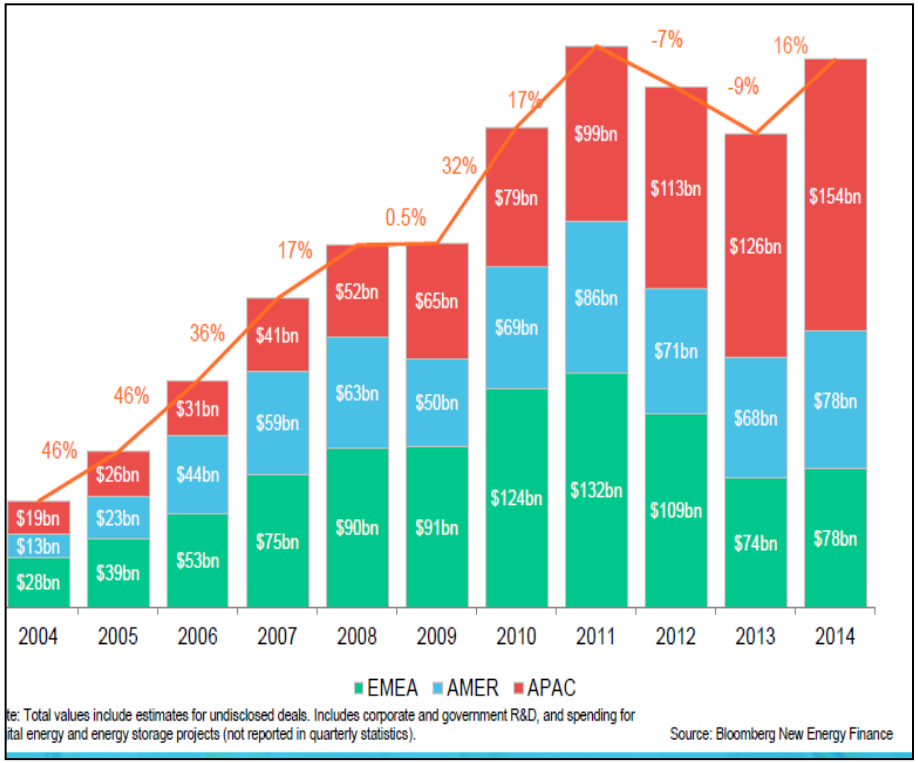
Global New Investment in Renewables



Note: Total values include estimates for undisclosed deals. Includes corporate and government R&D, and spending for digital energy and energy storage projects (not reported in quarterly statistics).

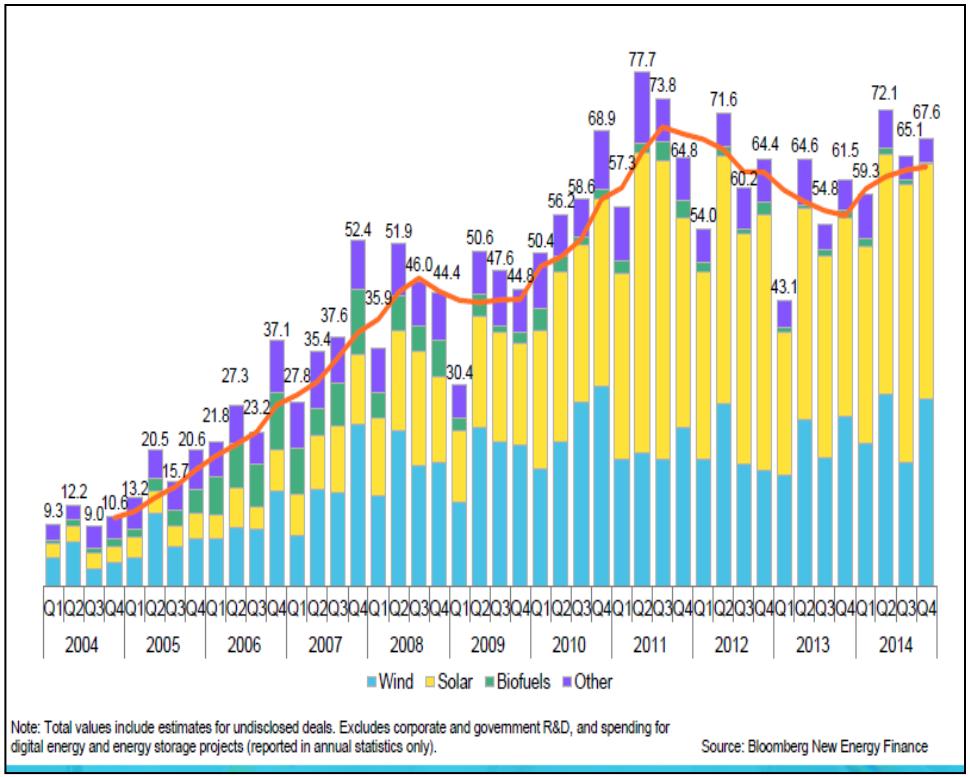
Source: Bloomberg New Energy Finance

New Investment by Region and Sector



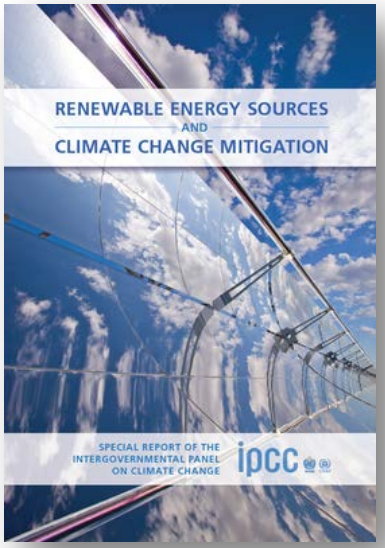
New Investment in Clean Energy by Region

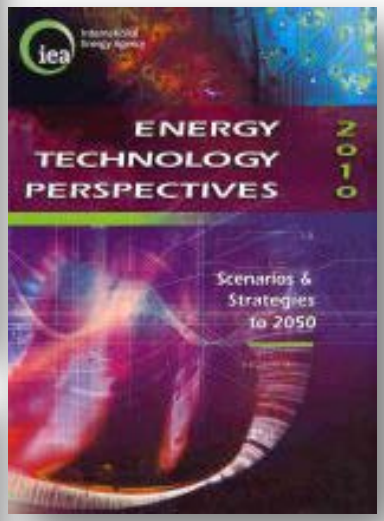
New Investment in Clean Energy by Sector

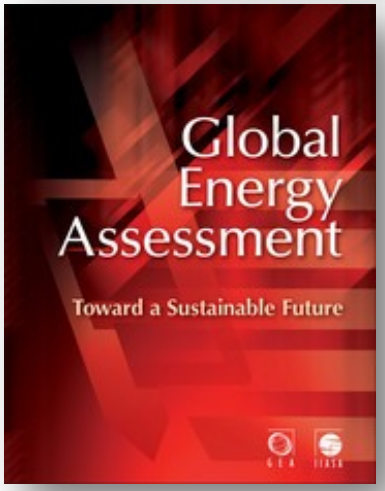


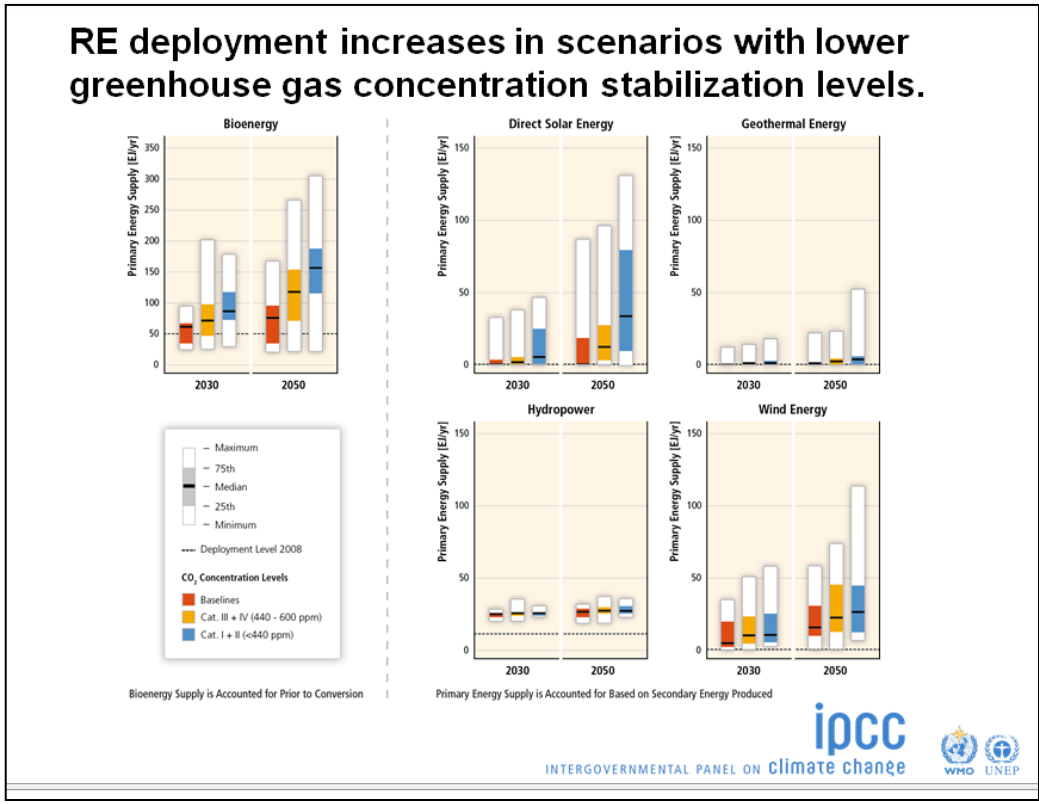
Source: http://about.bnef.com/presentations/clean-energy-investment-q4-2014-fact-pack/content/uploads/sites/4/2015/01/Q4-investment-fact-pack.pdf

Global Assessments of Renewable Energy Potential



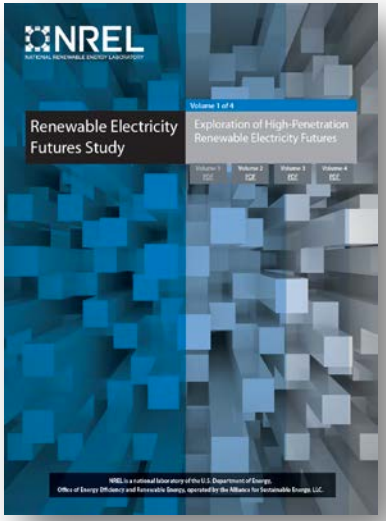


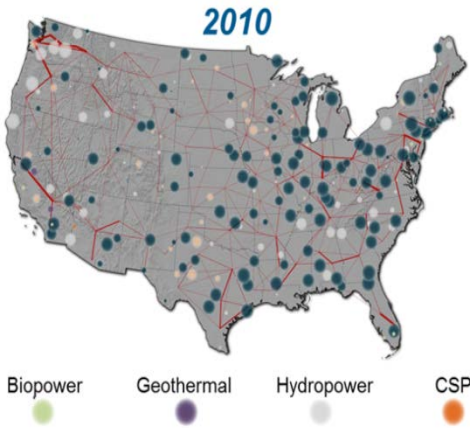


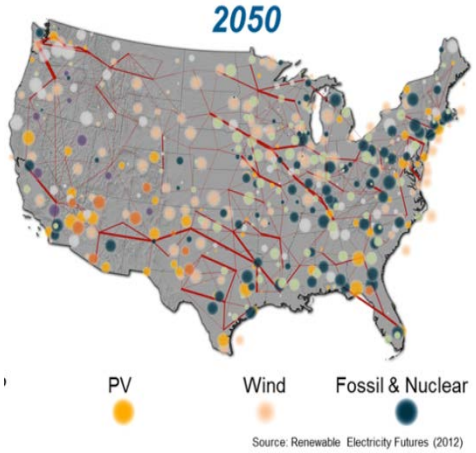


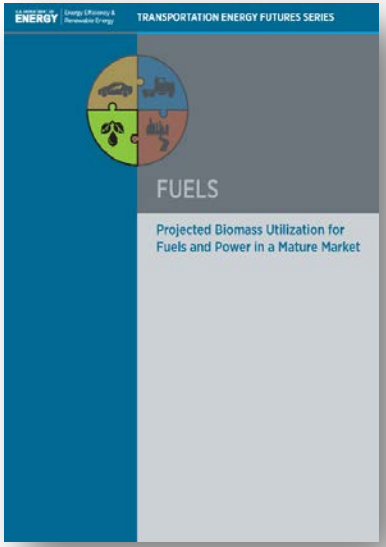
Technical potential for renewables is enormous.

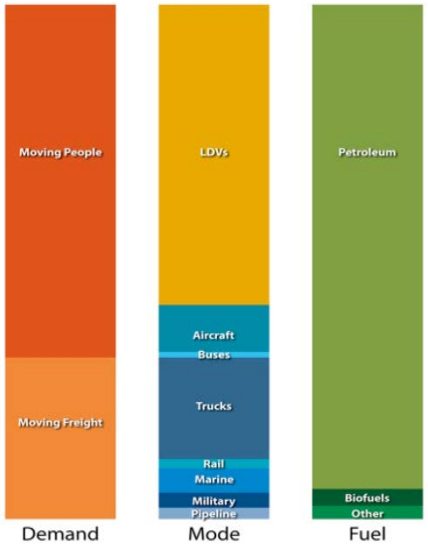
Comprehensive Studies Validate Opportunity for U.S. Renewables

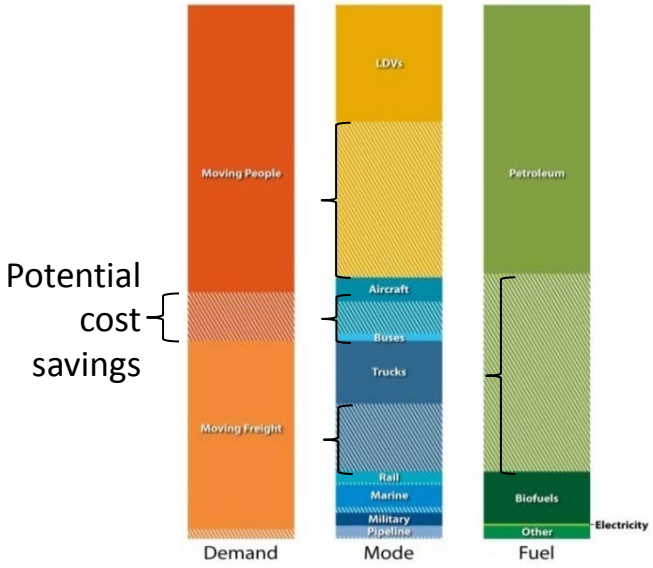


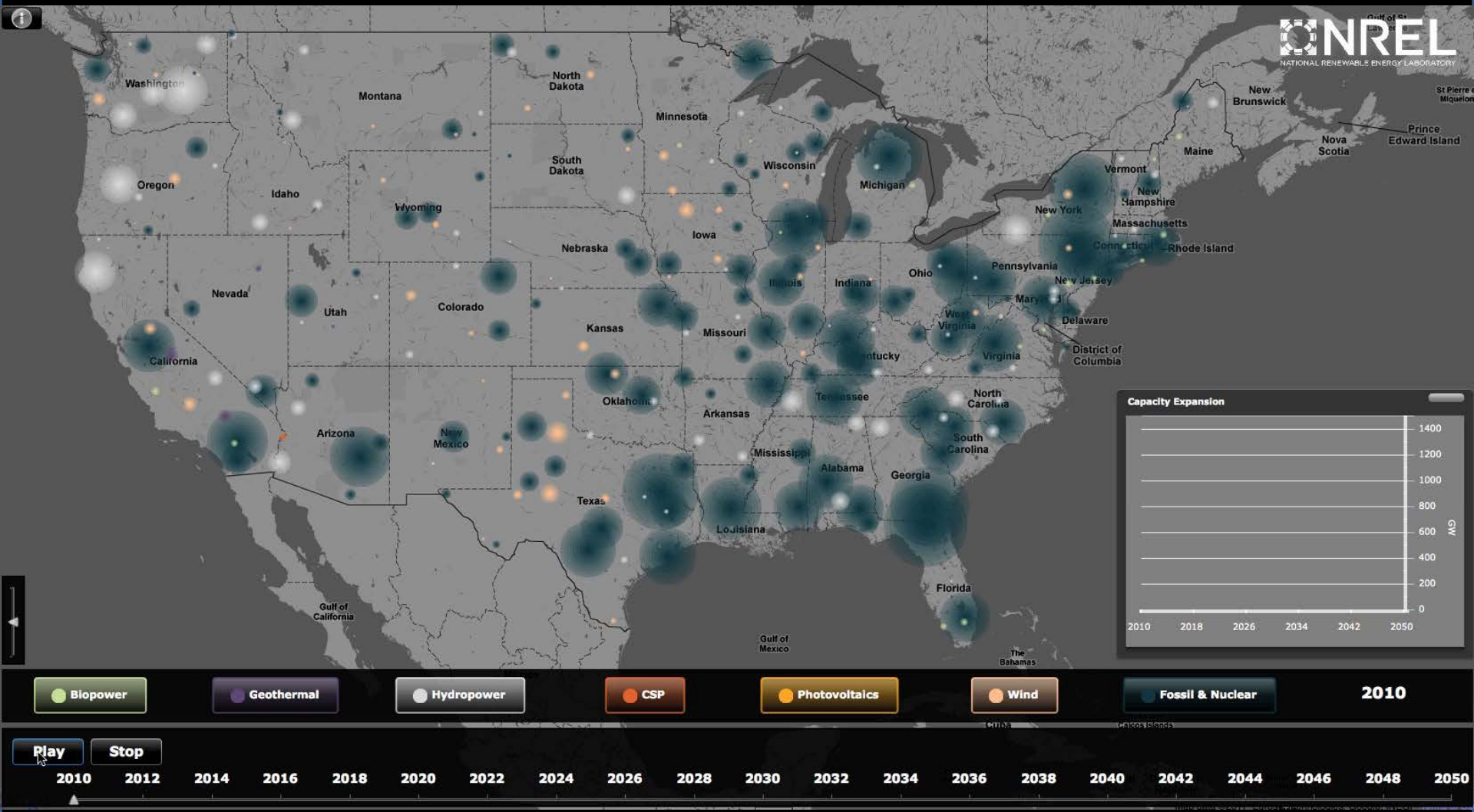











NREL
NATIONAL RENEWABLE ENERGY LABORATORY
Washington
Montana
North Dakota
Minnesota
Oregon
Idaho
South Dakota
Wisconsin
Michigan
Wyoming
Iowa
Nebraska
Nevada
Utah
Colorado
Kansas
Missouri
California
Oklahoma
Arkansas
Arizona
New Mexico
Mississippi
Alabama
Georgia
Texas
Louisiana
Florida
Gulf of California
Gulf of Mexico
The Bahamas
New Brunswick
Maine
Nova Scotia
Prince Edward Island
Vermont
New Hampshire
New York
Massachusetts
Rhode Island
Pennsylvania
Ohio
Indiana
Illinois
New Jersey
Delaware
District of Columbia
Virginia
North Carolina
South Carolina
Capacity Expansion
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1000
800
600
400
200
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2010
2018
2026
2034
2042
2050
Biopower
Geothermal
Hydropower
CSP
Photovoltaics
Wind
Fossil & Nuclear
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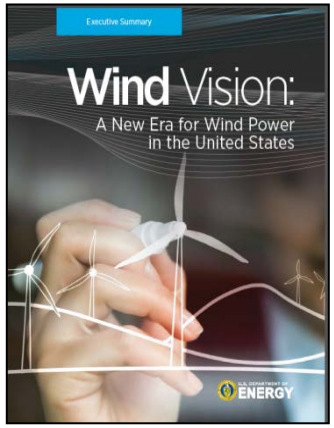
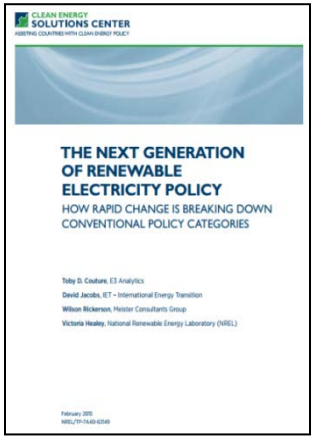
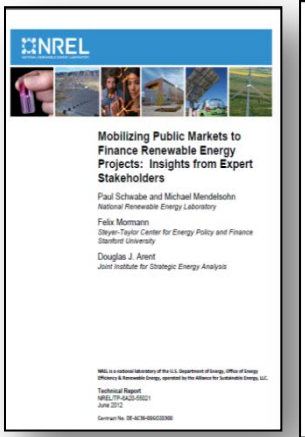
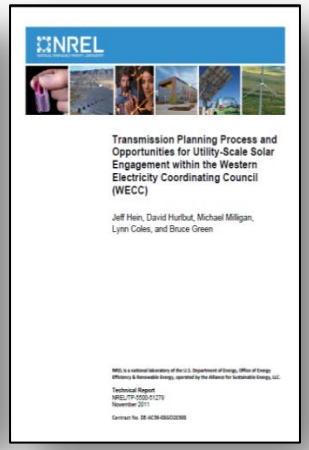
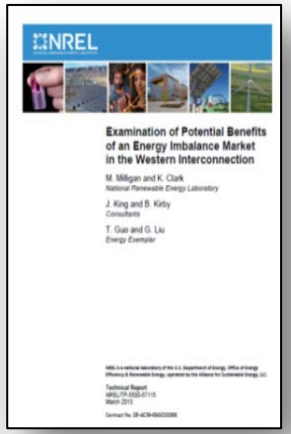
Looking Toward Implementation

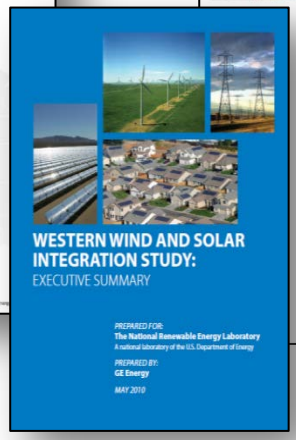


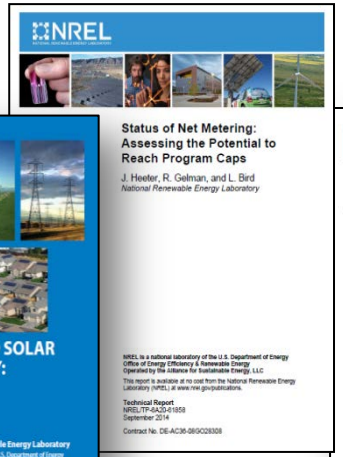


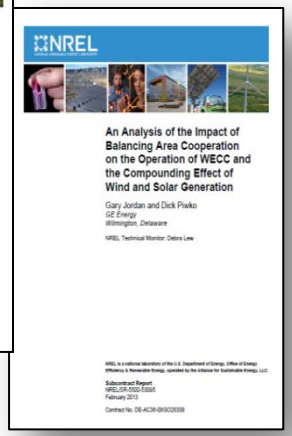












- Benefits of distributed generation
- Economics of technical pathways
- Implications of high penetration renewables
- Value of regional cooperation

Innovation, Integration, and Adoption

Reducing Investment Risk

- Enable basic and applied clean energy technology innovation
- Accelerate technology market introduction and adoption
- Integrate technology at scale
- Encourage collaboration in unique research and testing “partnering” facilities

Mobilizing Capital

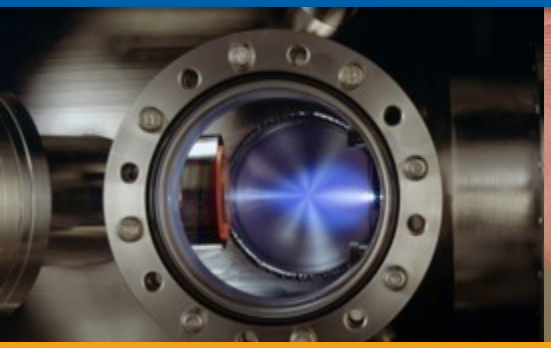
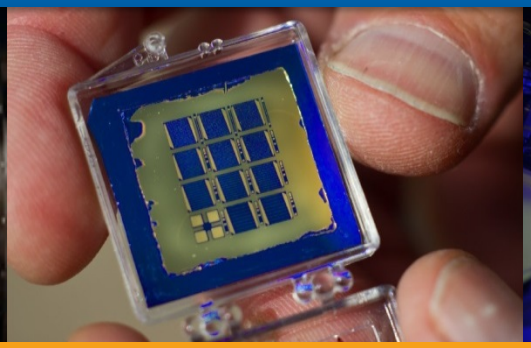
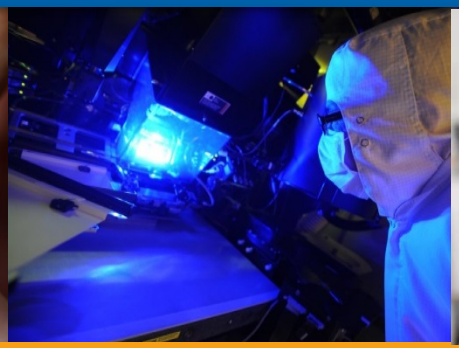
Commercial Partnerships

Technology Innovation

Sustainable
TRANSPORTATION

Renewable
ELECTRICITY GENERATION

Energy Saving
HOMES, BUILDINGS, & MANUFACTURING

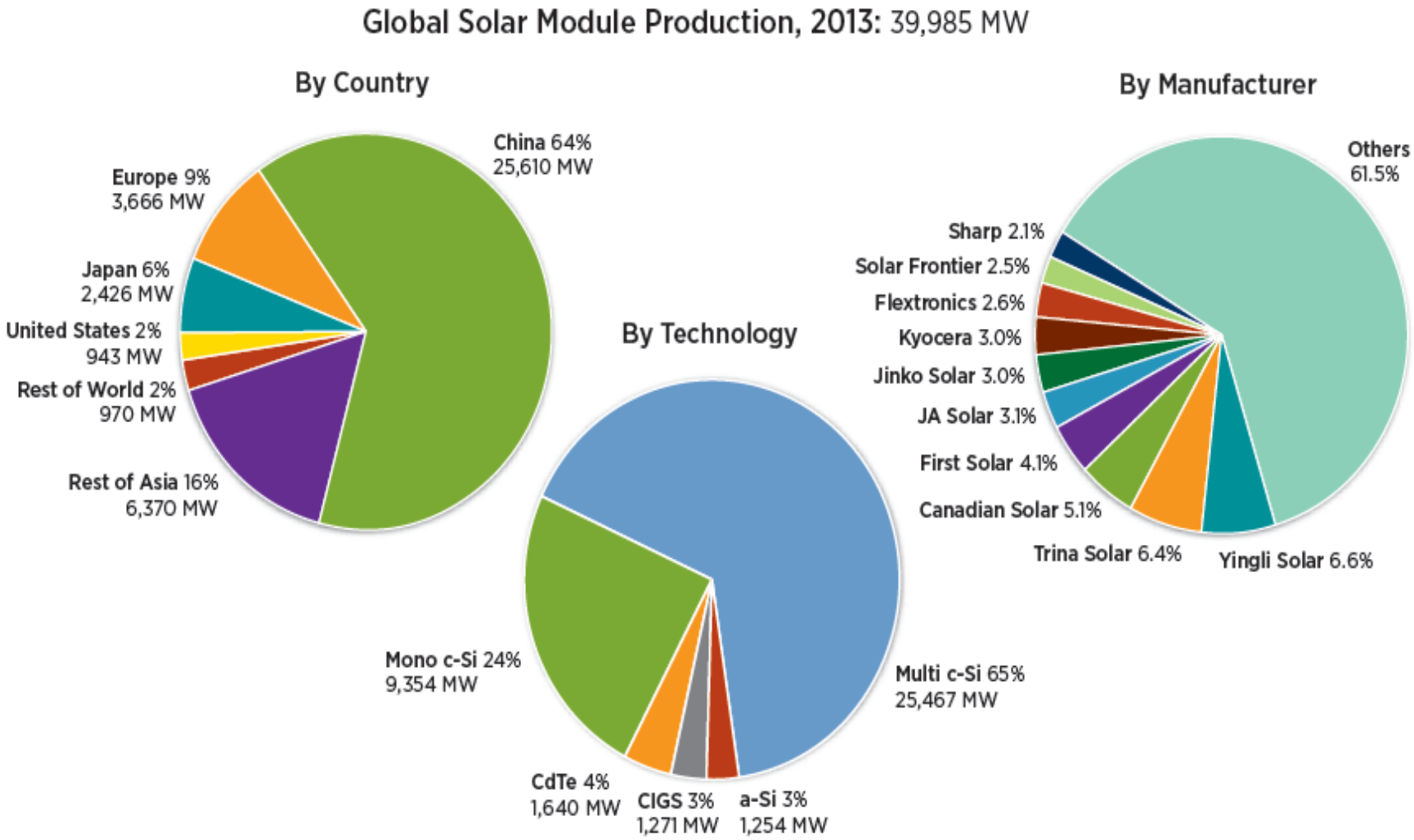





Market Impact

- U.S. Capacity:
  - 20 GW
  - <1% of U.S. power generation
  - <$2 to $6/W: LCOE 7 to 16¢/kWhr
- Global Capacity:
  - ~200 GW

Updated 3/10/2015

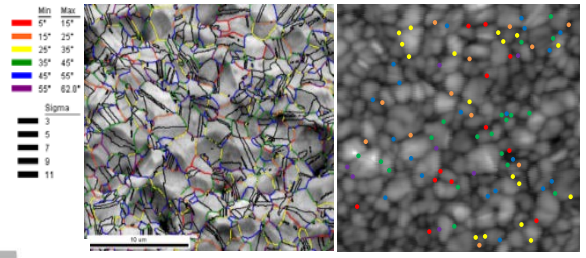
Worldwide PV Manufacturing

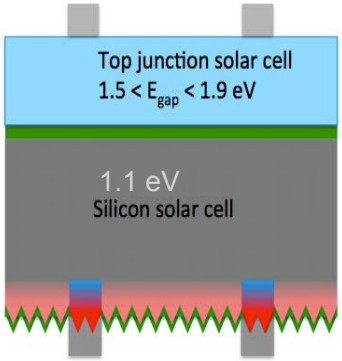


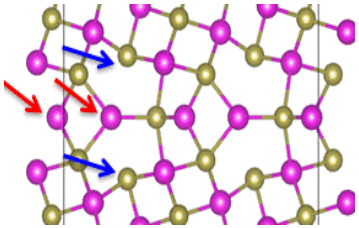
Source: NREL 2013 Data Book

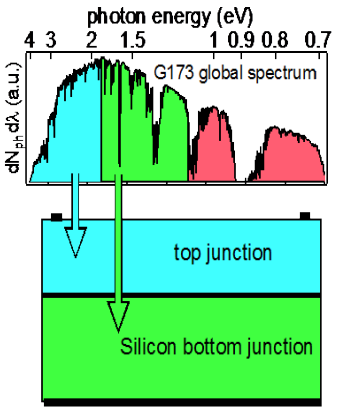
PV Technologies

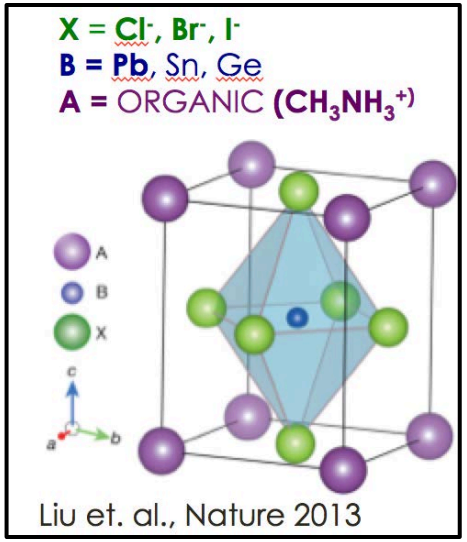
- High Efficiency Thin Films – Improved carrier lifetime and development of doping techniques will boost commercial module efficiency to 16%.
- Si Tandem Cells – Potential to increase the best cell efficiencies by 10%, to over 30%.
- Low Cost III-V 1J & 2J Cells – Potential to lower III-V growth cost by 1 – 2 orders of magnitude.
- "Kerfless Si" Wafers & Cells – Potential to cut supply chain capital investment by 50% with comparable cell performance.
- Perovskites – Very new polycrystalline thin film technology that has already demonstrated η > 17%.











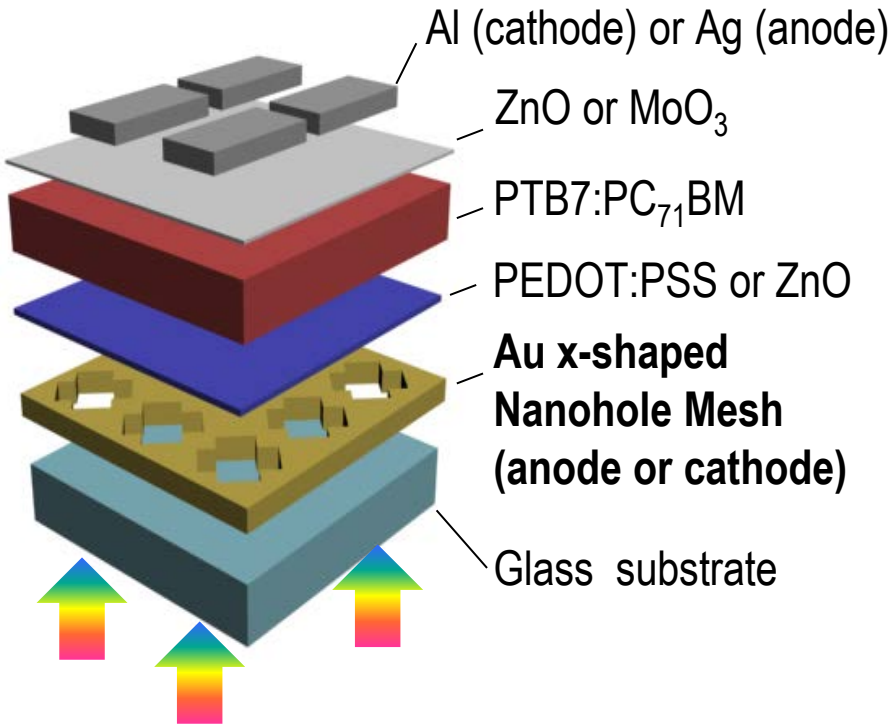
NSF Clean Energy Research: Optical and Nanostructural Control of Visibly-transparent Small-bandgap Excitonic Semiconductors For Integration in Highly-efficient Transparent Photovoltaics

Michigan State University, Award CBET- 1254662

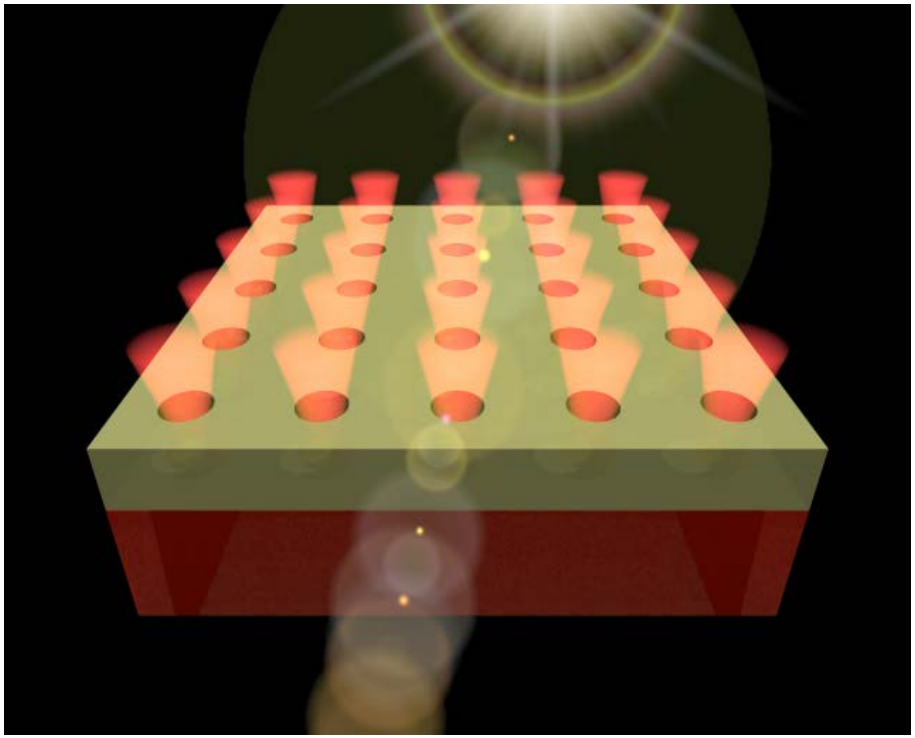
A transparent solar energy module that selectively captures infrared light is shown. These devices are creating a new paradigm and new markets for aesthetic solar energy harvesting

Art and Energy: High School Students use luminescent paints developed in our lab to paint colorful luminescent solar art paintings that can also generate electricity and inspire students in STEM

NSF Clean Energy Research

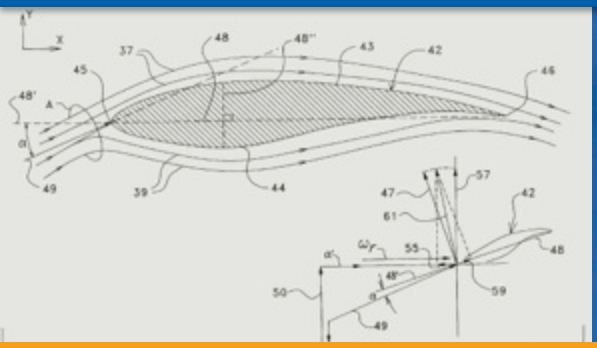


Plasmonic Wide Angle Light Concentrators for Bulk-Heterojunction Solar Cells University of Washington, Award CBET- 1346859



High Efficiency Photovoltaics Through Engineering Spontaneous Emission University of Maryland, Award CBET- 1335857

NREL Research: Wind

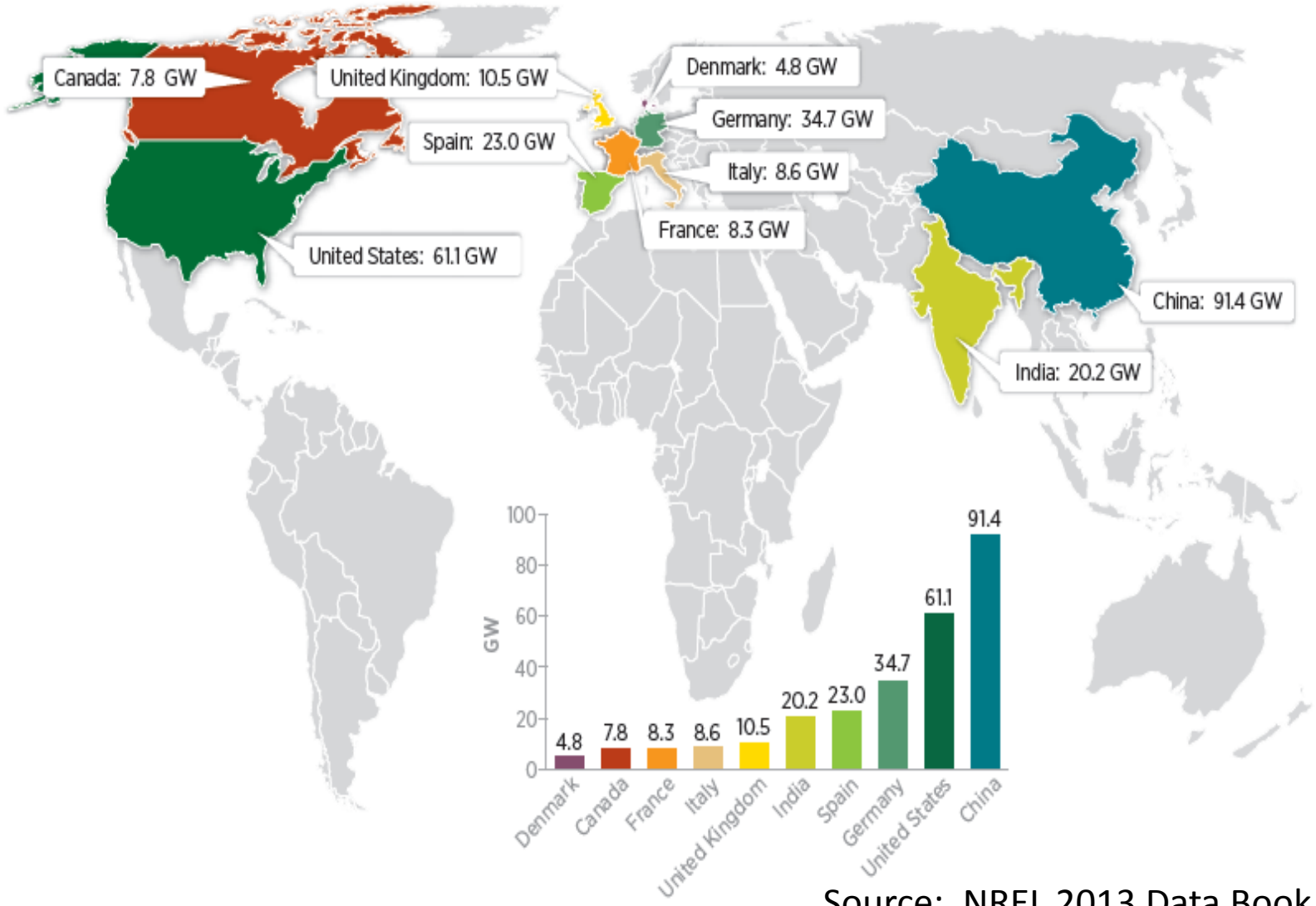


Market Impact

- U.S. Capacity:
  - 66 GW
  - 3-9 cents/kWh
  - Installed cost: $1.00-$1.90/W
- Global Capacity:
  - 370 GW

Updated 3/10/2015

Cumulative Wind Capacity – Top 10 Countries



Sources: LBNL, REN21
Includes offshore wind

57

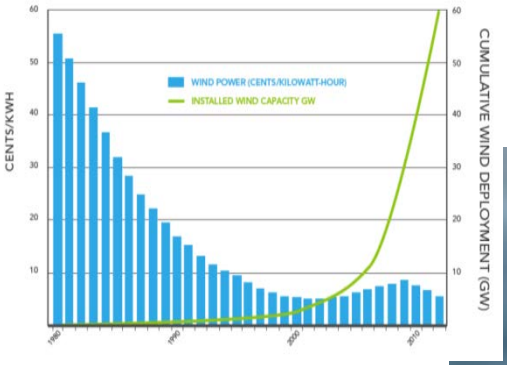
Source: NREL 2013 Data Book

Wind Technologies

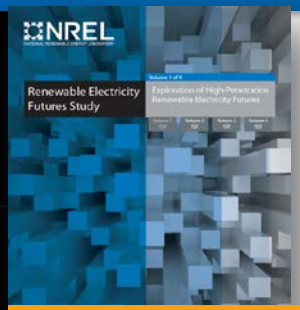
ATMOSPHERE TO ELECTRONS
U.S. DEPARTMENT OF ENERGY

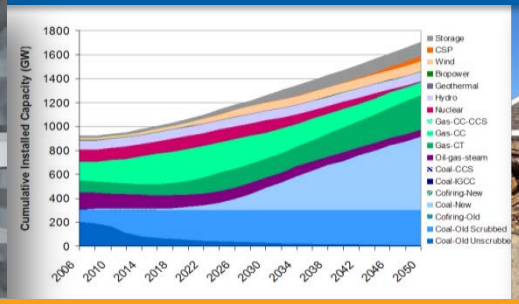
DOE Thrust: Atmosphere to Electrons

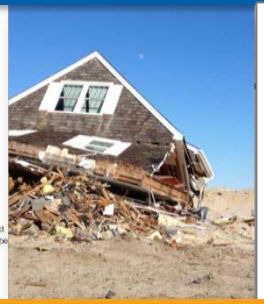
- Wind farm system improvements
- Component improvements
  - Modular large components – blades, drivetrains, and tall towers
  - Advanced drivetrain power conversion systems
  - Flexible, ultra-large rotors and systems
  - Active controls for structural load reduction, improved wind plant performance, and grid-friendly operation
  - Floating offshore wind turbines
  - Airborne wind power systems



NREL Research: Energy Analysis and Decision Support





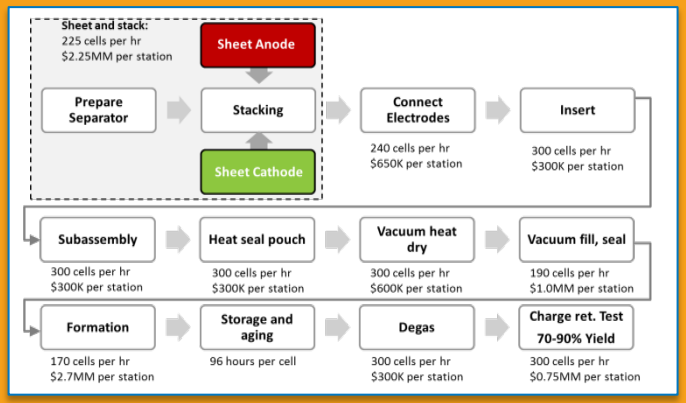


Knowledge in Context for Decision Makers

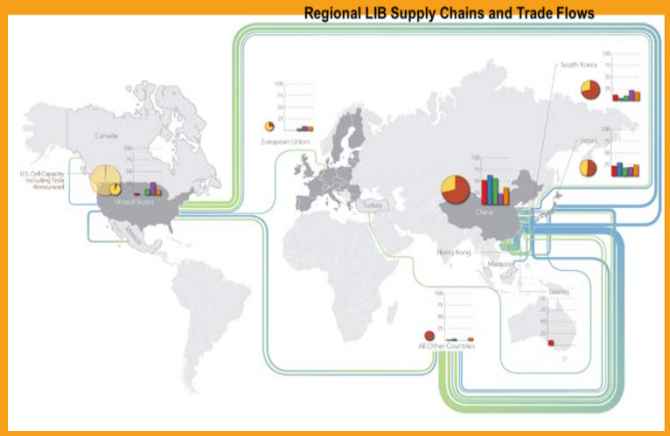
- **Techno-economic analyses identify R&D areas with high potential for impact**
- **Collaboration across national labs in support of the Quadrennial Energy Review (QER)**
- **Technical Assistance to FEMA and States in Rebuilding Following Weather Events/Disasters**
- **Analyses and Technical Knowledge Reduces Risk in Federal Investments**
  - Treasury 1603 Grants (Technical review of 98,816 clean energy projects to date, with $23 billion in funding)
  - Navy-NREL Joint Technology Demonstrations in Hawaii and Guam (direct, recurring annual savings of 1 GWh)
- **Joint Institute for Strategic Energy Analysis (JISEA)**
  - Integrates capabilities across institutions
  - Provides analyses and information on clean energy in context of other energy pathways (fossil and nuclear)

Clean Energy Manufacturing Analysis

Technoeconomic Analysis – Detailed Cost Models: LIB Cell Production Process

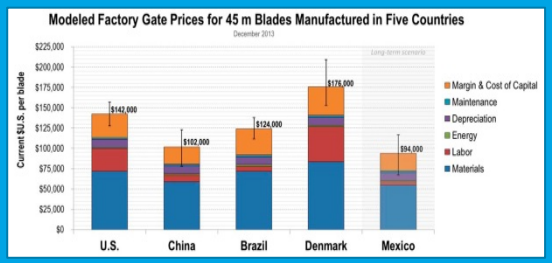


Global supply chain assessment

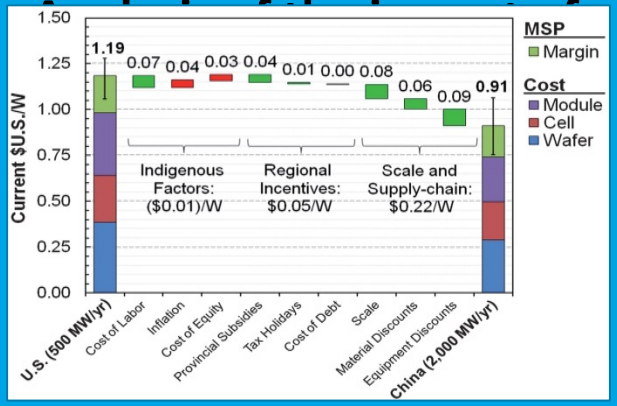


Chung, D.; Elgqvist, E. (2015). Automotive Lithium-ion Battery (LIB) Supply Chain and U.S. Competitiveness Considerations. NREL Report *in-press*.

Comparative cost analysis

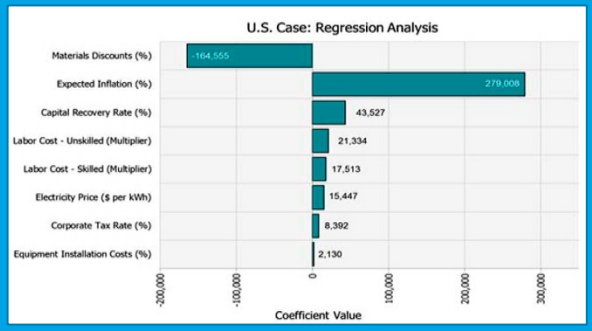


James, T.; Goodrich, A. (2013). Supply Chain and Blade Manufacturing Considerations in the Global Wind Industry (Presentation). NREL (National Renewable Energy Laboratory). 36 pp.; NREL Report No. PR-6A20-60063.



Goodrich, A. C.; Powell, D. M.; James, T. L.; Woodhouse, M.; Buonassisi, T. (2013). Assessing the Drivers of Regional Trends in Solar Photovoltaic Manufacturing. Energy and Environmental Science. Vol. 6(10), 1 October 2013; pp. 2811-2821; NREL Report No. JA-6A20-58652

Sensitivity analysis



James, T.; Goodrich, A. (2013). Supply Chain and Blade Manufacturing Considerations in the Global Wind Industry. NREL (National Renewable Energy Laboratory). 36 pp.; NREL Report No. PR-6A20-60063.

NREL Research: Energy Systems Integration



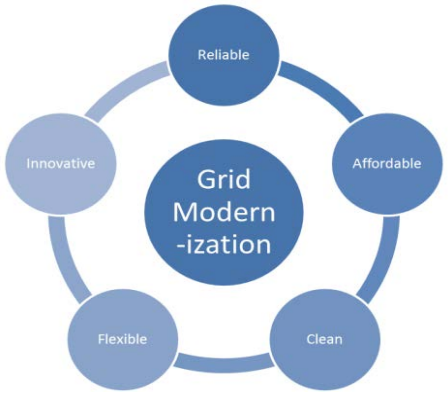
Early Impact

- New advanced inverters allow distributed generation to provide grid support
- Smart grid roll outs under ARRA
- IEEE Interconnection Standards
- 45 partners
- ~ $20M level of effort

The New Frontiers: Integration and Scale

- Integration of high-penetration renewables requires enhanced system-wide flexibility
  - Variable supply and variable load
  - Increased distributed resources
  - Enhanced energy imbalance market cooperation
  - Changing roles of consumers, utilities, investors, power providers, vendors, and regulators
- Regional considerations continue to drive progress
- Production scale and supply chain crucial to lower manufacturing costs
- Investment in technology R&D imperative
  - Better monitoring and measurements
  - Advanced analytics processing and control
  - Demand-shifting and load profile shaping techniques
  - Two way power flow control electronics

Key Attributes of a Modernized Grid



Sensing and Measurements	• Visualization tools that enable complete visibility of generation, loads and grid dynamics across the electric system
Devices and Integrated Systems	• Establish common test procedures and inter-operability standards for devices that can provide valuable grid services alone and/or in combination
System Operations and Power Flow	• Develop advanced real-time control technologies to enhance the reliability and asset utilization of T&D systems
Design and Planning Tools	• Create grid planning tools that integrate transmission and distribution and system dynamics over a variety of time and spatial scales
Security and Resilience	• Develop advanced security (cyber and physical) solutions and real-time incident response capabilities for emerging technologies and systems
Institutional Support	• Provide tools and data that enable more informed decisions and reduce risks on key issues that influence the future of the electric grid/power sector

Outreach in Colorado

CCIA
Colorado Cleantech Industry Association

Colorado
Office of Economic Development and International Trade

Governor's Energy Office

Metro Denver
Economic Development Corporation
Energetic Bodies. Energetic Minds.

colorado clean energy cluster
Empowering opportunities. Generating results.

Colorado Center for Renewable Energy Economic Development

Institute for ADVANCED
Composites Manufacturing
INNOVATION

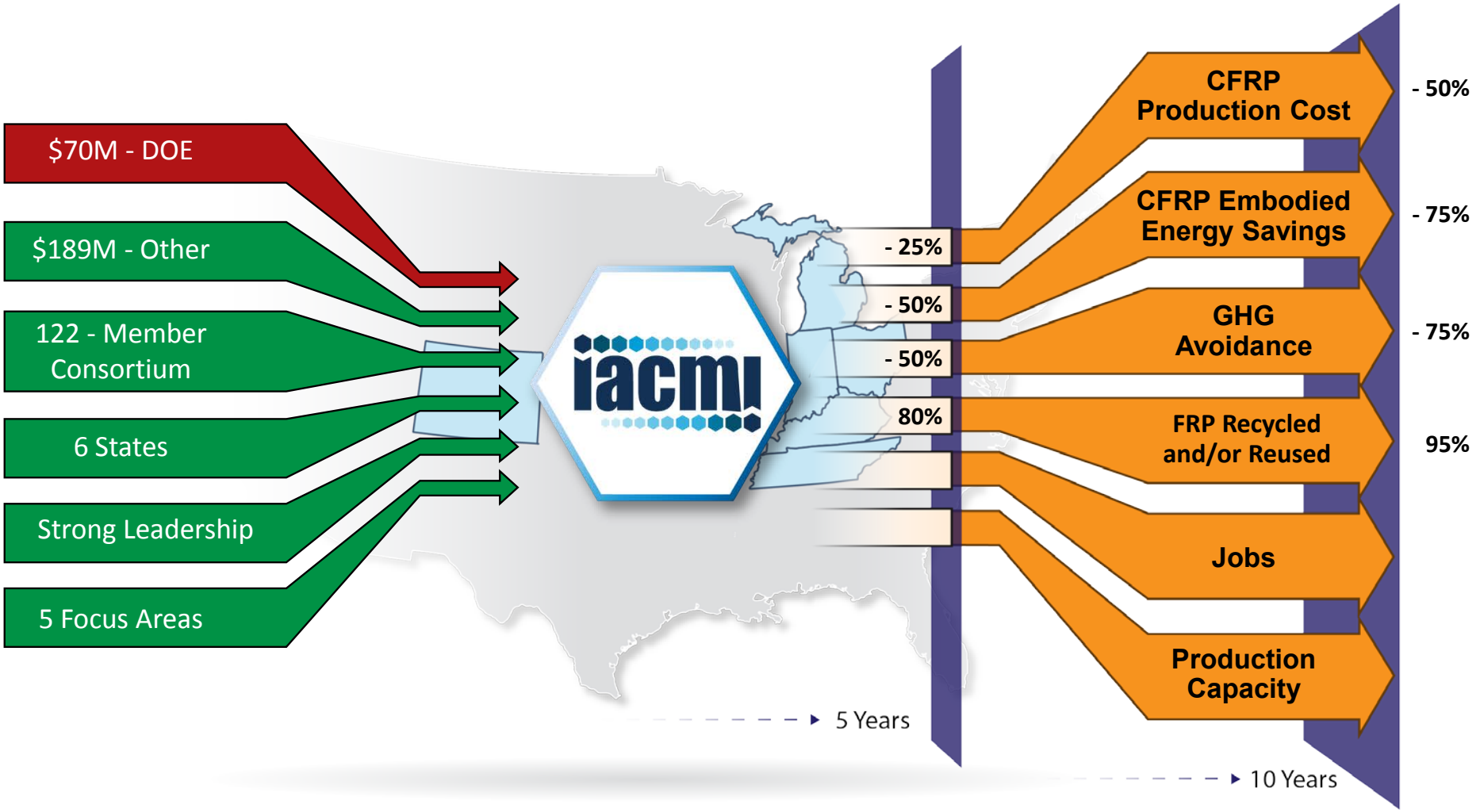
Shared RD&D facilities will support industry

Focus Areas

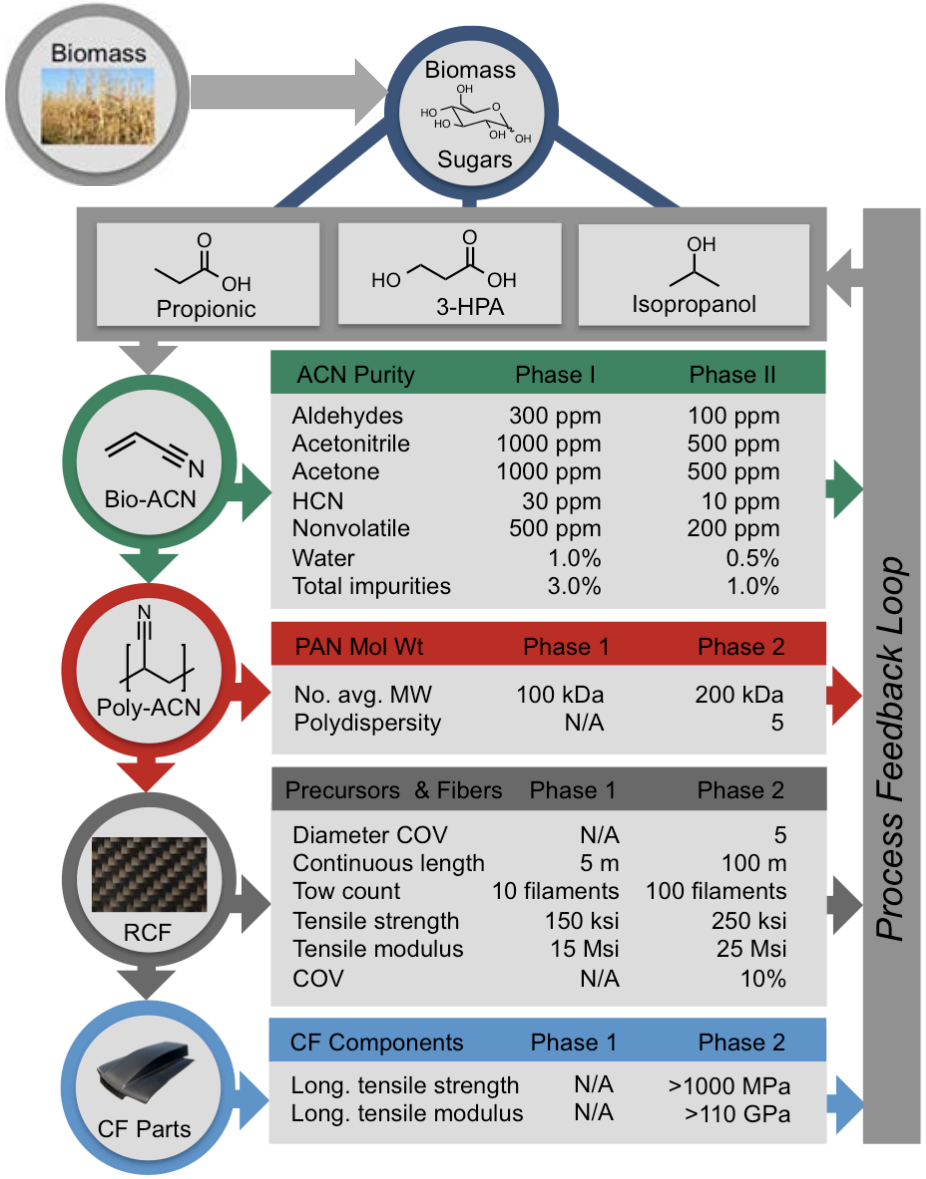
- **Vehicles** Michigan
- **Wind Turbines** Colorado
- **Composite Materials & Process Technology** Tennessee
- **Compressed Gas Storage** Ohio
- **Innovative Design, Predictive Modeling & Simulation** Indiana

iacmi

Federal investment will catalyze a composites ecosystem in the heart of US manufacturing



Renewable Carbon Fiber Consortium (RCFC)



ACN Purity	Phase I	Phase II
Aldehydes	300 ppm	100 ppm
Acetonitrile	1000 ppm	500 ppm
Acetone	1000 ppm	500 ppm
HCN	30 ppm	10 ppm
Nonvolatile	500 ppm	200 ppm
Water	1.0%	0.5%
Total impurities	3.0%	1.0%

PAN Mol Wt	Phase 1	Phase 2
No. avg. MW	100 kDa	200 kDa
Polydispersity	N/A	5

Precursors & Fibers	Phase 1	Phase 2
Diameter COV	N/A	5
Continuous length	5 m	100 m
Tow count	10 filaments	100 filaments
Tensile strength	150 ksi	250 ksi
Tensile modulus	15 Msi	25 Msi
COV	N/A	10%

CF Components	Phase 1	Phase 2
Long. tensile strength	N/A	>1000 MPa
Long. tensile modulus	N/A	>110 GPa

Lead: NREL

Partners: INL, Biochemtex, Johnson Matthey, CU, CSM, ORNL, MATRIC, DowAksa, Ford, MSU

Award: ~$6M for 40 months

Objective: Cost effective production of renewable carbon fibers from ligno-cellulosic biomass

Strategy:

- Deconstruction of biomass to sugars/lignin
- Biological production of key intermediates
- Chemical catalysis to acrylonitrile (ACN)
- Polymerization of ACN to Carbon Fiber for industrial testing and validation

To achieve a clean energy vision, we must…

Invest in innovation

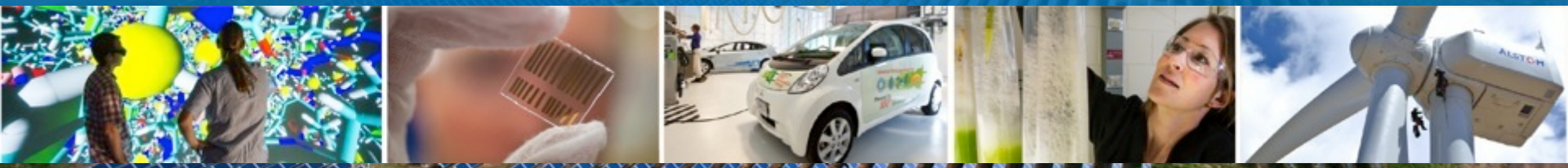
Invent the future we desire

Improve access to capital

Partner on a global scale

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

For more than 35 years, NREL has delivered innovation impact enabling the emergence of the U.S. clean energy industry.



For more information, please visit our website at
www.nrel.gov